STAFF SUMMARY SHEET

	TO	ACTION	SIGNATURE (Surname), GRADE AND DATE		TO	ACTION	SIGNATURE (Surname), GRADE AND DATE
1	DFAN	sig	Col 18 Apr 12	6			
2	DFER	approve	Col 19 Apr 2012	7			
3	DFAN	action	(Author /Originator)	8			
4				9			
5				10			

SURNAME OF ACTION OFFICER AND GRADE	SYMBOL	PHONE	TYPIST'S INITIALS	SUSPENSE DATE
Lt Col Hall	DFAN	333-8564	jkh	20120415

SUBJECT	DATE
Clearance for Material for Public Release USAFA-DF-PA-288	20120322

SUMMARY

1. PURPOSE. To provide security and policy review on the document at Tab 1 prior to release to the public.

2. BACKGROUND.
Authors: C1C Justin Mason, Lt Col James Hall,

Title: Autonomous Aileron Roll Control for Miniature Air Vehicles

Circle one: Abstract Tech Report Journal Article Speech Paper and Presentation Poster
Thesis/Dissertation Book Other: ____________

Check all that apply (For Communications Purposes):
[] CRADA (Cooperative Research and Development Agreement) exists
[] Photo/ Video Opportunities [] STEM-outreach Related [] New Invention/ Discovery/ Patent

Description: Abstract--As miniature air vehicles (MAVs) proliferate in various optical surveillance missions, the ability to autonomously avoid obstacles in the flight path using aerobatic maneuvering becomes more desirable. A basic aerobatic flight maneuver from which other maneuvers can be derived is the aileron roll. The aileron roll maneuver can be executed using a time -parametrized attitude trajectory generation algorithm in conjunction with an associated attitude tracking control law.

Release Information: To be presented at the AIAA Infotech@Aerospace Conference, Garden City, CA, 19-21 June 2012

Previous Clearance information: (If applicable): None.

Recommended Distribution Statement: Distribution A: approved for public release, distribution unlimited

3. DISCUSSION.

4. RECOMMENDATION. Sign coord block above indicating document is suitable for public release. Suitability is based solely on the document being unclassified, not jeopardizing DoD interests, and accurately portraying official policy.

Thomas E. McLaughlin, Ph.D.
Director, Aeronautics Research Center

paper

Autonomous Aileron Roll Control for Miniature Air Vehicles

James K. Hall* and Justin K. Mason†

March 22, 2012

Abstract

As miniature air vehicles (MAVs) proliferate in various optical surveillance missions, the ability to autonomously avoid obstacles in the flight path using aerobatic maneuvering becomes more desirable. A basic aerobatic flight maneuver from which other maneuvers can be derived is the aileron roll. The aileron roll maneuver can be executed using a time-parametrized attitude trajectory generation algorithm in conjunction with an associated attitude tracking control law. Additionally, by accounting for actual angle of attack of the MAV, the deviation from the initial flight path during an aileron roll maneuver can be decreased. However, to be successful, an attitude-based switching logic must be implemented in the control law to account for the arctangent range being undefined between for angles greater than 90 degrees causing control reversal during the inverted portion of the maneuver. The performance of our control algorithm during aileron roll maneuvers is demonstrated through computer flight simulations and flight tests.

1 Introduction

Miniature air vehicles (MAVs) are employed around the world in applications as diverse as tracking forest fire perimeters, searching for lost persons, and tactical reconnaissance for infantry operations. The development of various technologies such as low-cost, solid-state sensors and cameras, brushless electric motors, and light-weight, lithium-ion batteries has enabled the design and construction of simple, inexpensive, and capable MAVs. Operating MAVs in urban or mountainous environments is particularly challenging due to the obstacles that can be encountered at the typical flight altitudes. Therefore, much research is being conducted to develop technologies needed to autonomously avoid obstacles while traversing specified regions. One such technology is the ability to fly aggressive, aerobatic flight maneuvers.

For autonomous aircraft, the problem of avoiding obstacles has been addressed using several different approaches. An autonomous helicopter was used by [1] to autonomously explore an unknown urban environment by generating real-time, planar trajectories to navigate around obstacles. The work reported in [2] demonstrated the ability to generate paths for an aircraft flying among obstacles, and [3, 4] demonstrated the ability to plan and control planar trajectories to avoid obstacles. The common theme is the extension of terrestrial vehicle path planning to aircraft, inadvertently imposing an artificial constraint on the maneuver space. By developing autonomous aerobatic maneuver control, an aircraft's inherent ability to use altitude when avoiding obstacles can be exploited.

Autonomous aerobatic maneuvering has been addressed in the literature under the general category of motion planning. Specifically, an aerobatic flight maneuver is defined as a transition from one steady-state flight condition to another by passing through a sequence of desired locations, each with an associated attitude [5]. A library of autonomous flight maneuvers for small helicopters was presented in [6] and for high-powered, conventional-configuration MAVs in [7]. Both demonstrated that the continuous functions which specify an aerobatic flight maneuver must meet constraints on position and velocity at the beginning and ending of the maneuver.

Any library of aerobatic maneuvers for MAVs should include basic maneuvers such as an aileron roll. In [8], an aileron roll maneuver was commanded using a simple fifth-order polynomial to generate a time-parametrized trajectory in desired roll angle, which was fed into a maneuver control law to regulate the aircraft through the maneuver. Although the aileron roll maneuver was successfully demonstrated in simulation and flight tests, the aircraft lost a significant amount of altitude during the inverted portion of the maneuver. However, an important part of using aerobatic maneuvers to autonomously

*Assistant Professor, Department of Aeronautics, USAF Academy, james.hall2@usafa.edu

†Undergraduate Research Assistant, Department of Aeronautics, USAF Academy

avoid obstacles is tracking desired altitude with minimal error to avoid colliding with other obstacles. Thus, the next step is to develop a relationship between roll angle and pitch angle that minimizes altitude loss.

In addition to a medium fidelity Matlab flight simulation, the Brigham Young University (BYU) Multi-AGent Intelligent Coordination and Control (MAGICC) lab developed a high-fidelity flight simulation environment called Aviones. These two tool are utilized in developing autonomous aircraft control methodologies that can be programmed directly onto the MAV autopilot [9,10] for flight testing. This combination of tools allows the rapid development and refinement of improved control laws in simulation for subsequent flight demonstrations.

The time-parametrized attitude trajectory algorithm is presented in Section 2, and the trajectory tracking control law is presented in Section 3. The performance of the attitude trajectory generation and tracking algorithms are verified through flight simulations and flight tests, with the results shown in Section 4. Concluding remarks are found in Section 5.

2 Aileron Roll Attitude Trajectory

The aileron roll maneuver presented in [8] was created using a time-parametrized trajectory in roll angle, ϕ^d, which was generated from a fifth-order polynomial function [11]. This polynomial function has two attractive properties: 1) the desired angle and its first derivative are continuous, smooth functions, and 2) they are easily generated at each time step in the autopilot code. For the aileron roll maneuver, the functions defining the desired roll angle and first derivative are

$$\phi^d(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5 \qquad (1)$$
$$\dot{\phi}^d(t) = a_1 + 2a_2 t + 3a_3 t^2 + 4a_4 t^3 + 5a_5 t^4, \qquad (2)$$

where the subscript d indicates the desired value. For a lateral-axis-only maneuver (aileron roll), the derivative of the roll angle, $\dot{\phi}^d$, is assumed to be approximately equal to the angular rate about the body-frame x-axis, commonly denoted as p. The polynomial coefficients (a_n, $n = 1, ..., 5$) are calculated from the boundary conditions on the roll angle and its first two derivatives, according to the equations:

$$\begin{aligned}
a_0 &= \phi_0 \\
a_1 &= \dot{\phi}_0 \\
a_2 &= \frac{\ddot{\phi}_0}{2} \\
a_3 &= \frac{20(\phi_f - \phi_0) - \left(8\dot{\phi}_f + 12\dot{\phi}_0\right) t_f + \left(\ddot{\phi}_f - 3\ddot{\phi}_0\right) t_f^2}{2t_f^3} \\
a_4 &= \frac{30(\phi_0 - \phi_f) + \left(14\dot{\phi}_f - 16\dot{\phi}_0\right) t_f - \left(2\ddot{\phi}_f - 3\ddot{\phi}_0\right) t_f^2}{2t_f^4} \\
a_5 &= \frac{12(\phi_f - \phi_0) - \left(6\dot{\phi}_f + 6\dot{\phi}_0\right) t_f + \left(\ddot{\phi}_f - \ddot{\phi}_0\right) t_f^2}{2t_f^5},
\end{aligned} \qquad (3)$$

where the subscript 0 indicates an initial condition ($t = 0$) and subscript f indicates a final condition ($t = t_f$).

With this formulation, an aileron roll maneuver can be flown by specifying that $\phi_0 = 0$ and $\phi_f = 2\pi$. Thus, the trajectory in roll angle completes a full revolution and the aircraft tracking these angles will fly an aileron roll maneuver. The aggressiveness of the maneuver is specified by final time (t_f), where a smaller t_f results in faster turning. For the MAGICC lab MAVs, the limits on t_f were found through multiple trials of simulated flight maneuvers.

An ideal aileron roll never deviates from a single heading, altitude, or velocity; however, the lack of control on pitch angle resulted in the significant altitude loss for the aileron roll maneuver reported in [8]. The control law performance during the aileron roll maneuver can be improved by finding a relationship for desired pitch angle as a function of the desired roll angle produced by Equation (1). This relationship can be derived from the change in altitude equation of motion [12], which can be written as

$$\dot{h} = u \sin\theta - v \sin\phi \cos\theta - w \cos\phi \cos\theta, \qquad (4)$$

where θ is the pitch angle, ϕ is the roll angle, and u, v, and w are the three body-frame components of the aircraft velocity vector. By setting the desired change in altitude equal to zero and assuming knowledge of the current body-frame velocities,

the roll angle can be set equal to the desired roll angle at the current time-step, allowing the calculation of a desired pitch angle using the expression

$$\theta^d = \tan^{-1}\left[\frac{1}{u}\left(v\sin\phi^d + w\cos\phi^d\right)\right]. \tag{5}$$

Equation (5) gives an equation for the desired pitch angle which should theoretically hold altitude constant during the entire maneuver, thus reducing the deviation from the initial flight path.

When this concept was first tested in the autopilot, however, the MAV flew completely off course, not only losing altitude but finishing the maneuver heading in the opposite direction, as shown in Figure 1. Part of the error was caused by failing to account for ambiguity in the Euler angle representation of attitude when an aircraft passes 90 degrees of roll angle and becomes inverted. Additionally, we assumed that the MAV axis of rotation for the aileron roll (the body-frame x-axis) was perfectly aligned with the velocity vector, implying that both pitch angle, θ, and angle of attack, α, were approximately equal to zero for straight, level flight. In reality, the MAV actually maintains approximately $\alpha = 4^o$ for constant-altitude, trimmed flight.

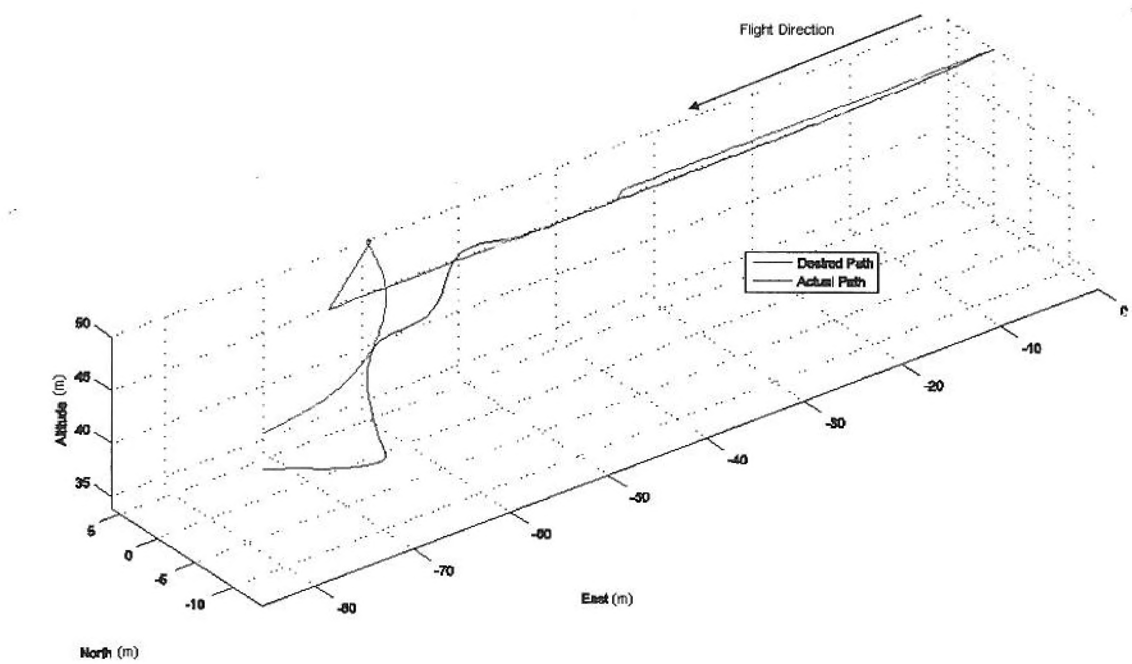
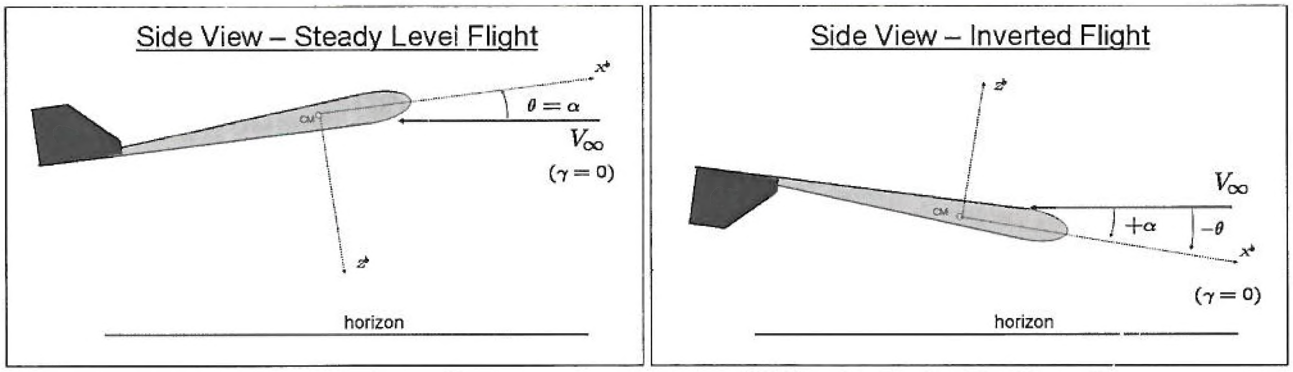


Figure 1: The dramatic deviations from the straight-and-level flight path were caused by the pitch angle sign change when rolling from normal to inverted flight.

Recognizing that the aircraft actually rotates about its velocity vector, not the body-frame x-axis, during an aileron roll requires understanding the relationship between angle of attack, α, and the Euler angle for pitch, θ. Angle of attack is the angle between the aircraft body-frame x-axis and the aircraft velocity vector, and the Euler angle, θ, relates the orientation of the body-frame x-axis to the inertial reference frame. Thus, in our initial trial, as the aircraft rolled about the velocity vector, from upright to inverted flight, the positive α was preserved, while θ changed sign from positive to negative. The initial and midpoint attitude of the MAV for the failed maneuver is shown in Figure 2. Here is the key point: to maintain altitude during an aileron roll maneuver, the control input to the elevator needs to cause a moment that raises the MAV's nose in the inertial reference frame regardless of orientation, thus when the aircraft is inverted the controller must command a negative angle of attack and a positive pitch angle.



(a) MAV prior to executing the aileron roll maneuver. (b) MAV at the mid-point of the aileron roll maneuver.

Figure 2: The MAV rotates about the velocity vector, which creates lift in the downward direction at the mid-point of the maneuver causing a decrease in altitude.

Hence, to maintain altitude during the aileron roll maneuver, the desired pitch angle must always be positive. This change of sign in the pitch angle θ^d becomes problematic for the maneuver tracking autopilot algorithm. For this reason, Equation (5) should be written as

$$\theta^d \quad = \quad \text{abs}\left(\tan^{-1}\left[\frac{1}{u}\left(v\sin\phi^d + w\cos\phi^d\right)\right]\right). \tag{6}$$

Therefore, when the aircraft is inverted, positive θ^d results in a negative α, resulting in a force that acts in the negative body-frame $\mathbf{z}$ direction, which is upwards in the inertial reference frame.

3 Altitude-Hold Aileron Roll Control Law

The attitude tracking control law was formulated using a simple proportional-derivative (PD) approach with gains that can be tuned for a specific aircraft maneuver envelope and the desired maneuver aggressiveness. Defining ϕ as the roll angle, p as the roll rate, k_ϕ as the control gain on the roll angle error and k_p as the control gain on the roll rate error, the original control law for the aileron roll was

$$\delta_e \quad = \quad 0 \tag{7}$$
$$\delta_a \quad = \quad k_\phi\left(\phi_d - \phi\right) + k_p\left(p_d - p\right), \tag{8}$$

where δ_e is the commanded elevator deflection and δ_a is the commanded aileron deflection. As discussed in Section 2, the control law required assuming that the rotation was about the body-frame $\mathbf{x}$-axis, implying that $\dot{\phi}$ was equal to the angular rate about the longitudinal axis, p. Although the vector alignment assumption causes poor performance for maintaining altitude, this assumption is sufficiently accurate to provide rate damping. Given the relationship between desired roll angle, ϕ^d, and desired pitch angle, θ^d, the aileron roll control law can now be written as

$$\delta_e \quad = \quad k_\theta\left(\theta^d - \theta\right) \tag{9}$$
$$\delta_a \quad = \quad k_\phi\left(\phi^d - \phi\right) + k_p\left(p^d - p\right). \tag{10}$$

Having established that θ^d being fed into the control law must always be positive, thus, when the roll angle is in the range $90^o \geq |\phi| \geq -90^o$, the desired roll angle for the control law should be negated which will drive the aircraft to a negative angle of attack and maintain altitude.

The three control law gains (k_ϕ, k_p, k_θ) must be tuned for the specified maneuver aggressiveness and airframe turn rate characteristics. In addition to tuning the controller gains, the maneuver aggressiveness variable (t_f) can be adjusted to ensure the aircraft has sufficient control authority to complete the maneuver.

Algorithm 1 Improved Aileron Roll Maneuver Control	

Calculate ϕ_d from Equation (1).
Calculate $\dot{\phi}_d$ from Equation (2).
Calculate θ_d from Equation (6).
if $90^o \geq |\phi| \geq -90^o$, then $\theta_d = -\theta_d$

4 Simulation and Flight Results

The improved aileron roll maneuver control law was developed and refined initially using a Matlab flight simulation. Subsequently, the control law algorithm was adapted into autopilot computer code syntax and modified for the aircraft sensors prior to flying the maneuver simulations in Aviones. Finally, the maneuver code was loaded onto the autopilot and demonstrated in actual flight tests using a MAGICC Lab MAV.

4.1 Matlab Simulations

The Matlab flight simulation incorporates the attitude quaternion-based six-degree-of-freedom aircraft equations of motion presented in [13]. The Matlab simulation environment provides a relatively quick method to develop and test new aircraft control concepts. Once the pitch angle sign change was incorporated into the aileron roll controller, the aileron roll maneuver in Matlab was superb. The revised control law was able to maintain the desired altitude to within two meters, as shown in Figure 3. Additionally, the lateral deviation from the original flight path was also less than two meters, compared with a deviation of over five meters of the original aileron roll algorithm.

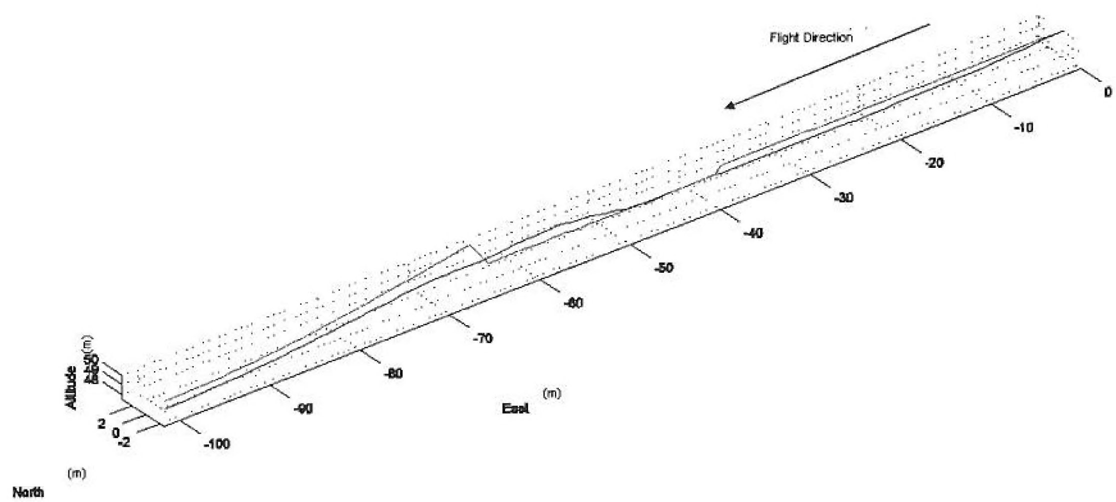


Figure 3: An aileron roll maneuver ($t_f = 2$) was flown autonomously in the Matlab flight simulator, where the pitch angle was used to minimize the deviation from the original path.

4.2 Aviones Simulations

One of the challenges for incorporating the improved aileron roll control law into the autopilot computer code was that the body-frame velocities u, v, and w were not measured directly on the aircraft. These three velocities are used in Equation 6 to calculate the desired pitch angle. For the short duration of an aerobatic flight maneuver, the MAV accelerometers can be integrated to find the three body-frame velocities given an accurate initial value.

Rather than employing the Euler integration method, we chose to use Heun's method (http://calculuslab.deltacollege.edu/ODE/7-C-2/7-C-2-h.html) which increases accuracy with minimal increase in computational load. Heun's method uses the average of the slopes at the current time step and the next time step to compute the next value. Taking an average of the two slopes produces an answer more accurate than Euler's method, essentially acting as a filter for high frequency noise. The formula

for Heun's Method can be written as

$$x_{k+1} = x_k + \frac{Ts}{2}\left[x_k^{'} + x_{k+1}^{'}\right]. \tag{11}$$

For this numerical integration technique, the initial values of the u, v, and w velocities are assumed to be those for an aircraft in steady, level flight. This implies that v is equal to zero. The airspeed, V_a, is measured by the dynamic pressure sensor, but α of the aircraft is needed to obtain u and w from V_a. Given that the flight path angle, γ, is zero at steady, level flight and using the relationship, $\theta = \gamma + \alpha$, means that θ is equal to α prior to the maneuver, which allows the body-frame velocities to be found using inertial-frame angles, or $u = V_a \cos\theta$ and $w = V_a \sin\theta$.

There is a weakness to this approach; the numerical integration to find the body-frame velocities $\left(\begin{bmatrix} u & v & w \end{bmatrix}^T\right)$ introduces lag in the control law, which can have a real impact for aerobatic flight maneuvers. Given this challenge, the autopilot version of the control law is unable to track the aileron roll maneuver as well as the Matlab version. The path of the MAV flying the aileron roll maneuver in the Aviones flight simulator can be seen in Figure 4.

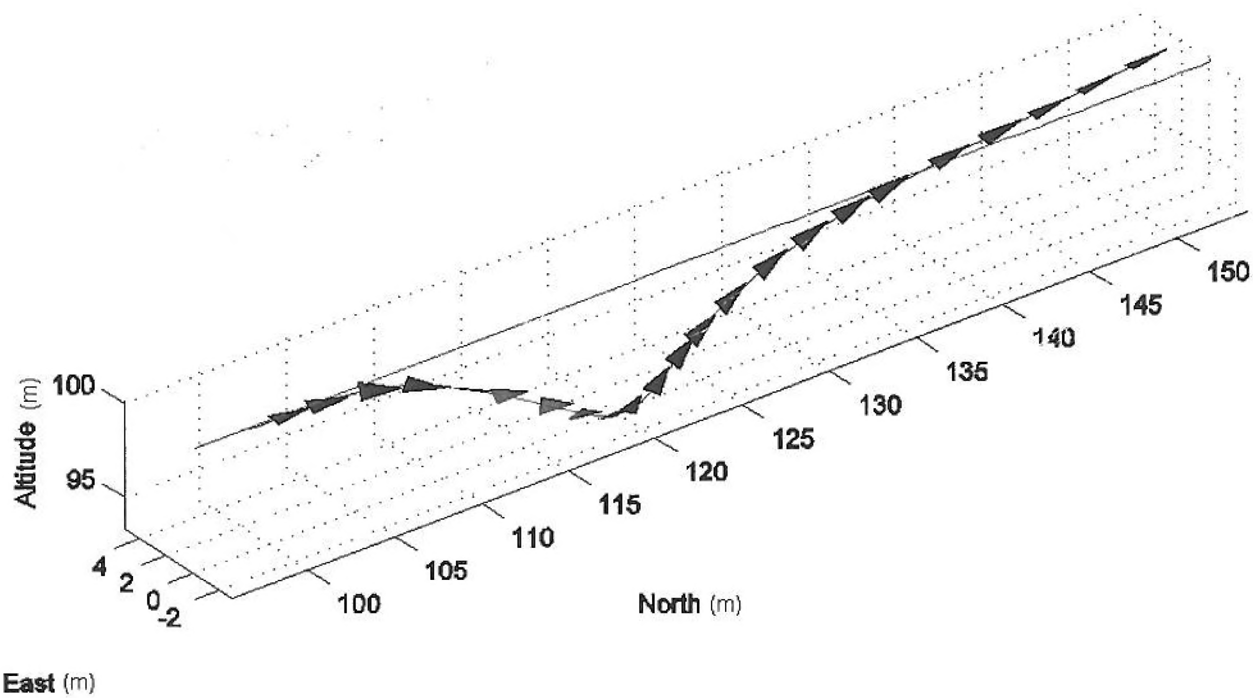


Figure 4: An aileron roll maneuver ($t_f = 2$) was flown autonomously in the Aviones flight simulator. The bi-colored triangles indicate the aircraft orientation at various positions during the maneuver.

Multiple runs of the aileron roll maneuver were conducted to tune the control law gains. The performance metric used was total distance deviation from the original flight trajectory. Figure 5 shows the total error for three different simulated aileron rolls. Once an optimal value for the pitch angle error gain was determined, the control law was ready for flight testing on the MAGICC Lab MAV.

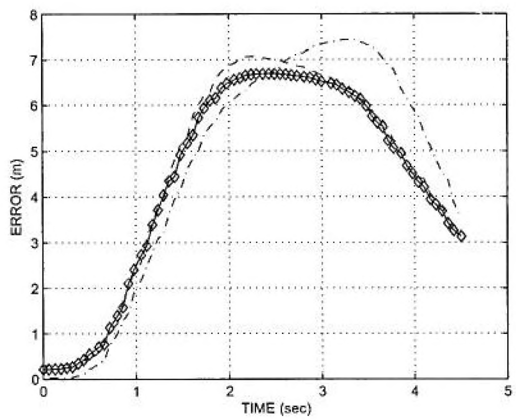


Figure 5: Three simulated aileron rolls were flown, each with a different k_θ gain value. The combined distance, vertical and lateral, from the original flight path was plotted to determine the optimal gain value.

4.3 Flight Tests

The flight testing was conducted at the USAF Academy where the field elevation is 7,250 feet. In spite of the high elevation, the aircraft flew well and the improved maneuver control law was able to track the roll angle trajectory with little deviation from the original path, as shown in Figure 6. The altitude lost was half that lost by the original attitude tracking control law, but the control law performance could be improved by additional flight tests during which the k_θ gain could be tuned for the actual hardware and air density as opposed to the MAV and environment modeled in Aviones.

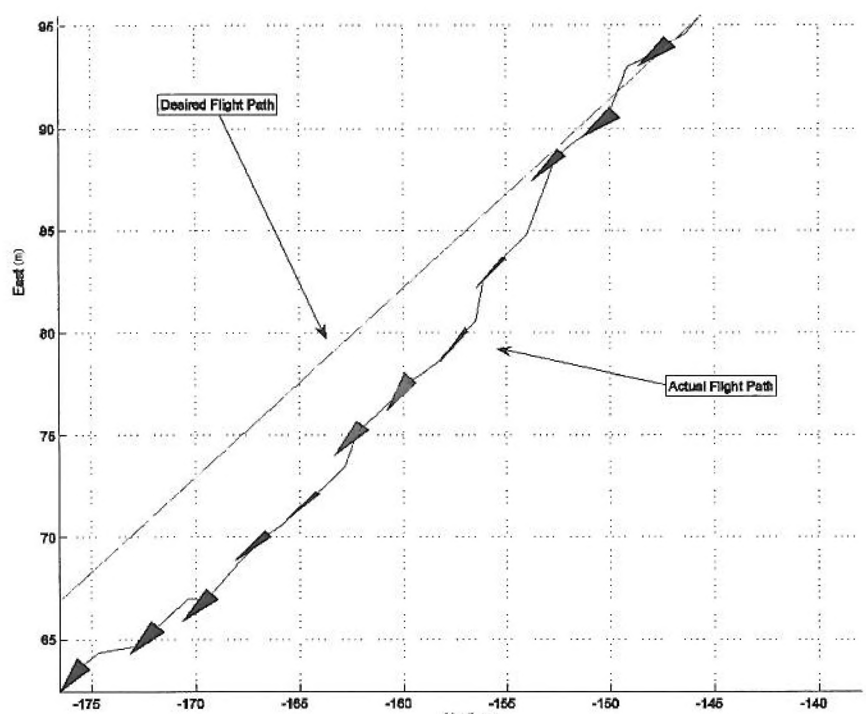


Figure 6: An aileron roll maneuver ($t_f = 2$) was flown autonomously over the USAF Academy athletic fields. The bi-colored triangles indicate the aircraft orientation at various positions during the maneuver and the red line indicates the original flight path.

Since the MAGICC Lab MAV does not have a rudder, the only control surfaces available to keep the aircraft from losing altitude are the elevons, the same control surfaces providing the roll moment. Saturating the aileron command automatically takes away from the ability of the control surface to input an elevator command and vice versa. The aileron and elevator commands shown in Figure 7 show the aileron command fluctuating dramatically, indicating that the roll angle gain, k_ϕ, can be reduced. Conversely, the very small angle deflections of the elevator commands indicate that the pitch angle gain, k_θ, could be increased.

The discrepancy in the performance of the flight test versus the Aviones simulation can be attributed to several sources. First, the air density used in Aviones is standard day atmospheric conditions at sea-level and the flights took place at an elevation over 7,000 feet. This difference in air density will cause the MAV elevons to behave differently, which can be compensated for by tuning the control gains. Secondly, the lag introduced by the numerical integration will be greater on the aircraft than in the simulation due to the much slower processor speed of the autopilot compared to the desktop computer. Finally, the noise on the accelerometers can effect the calculation of the body-frame velocities, negatively impacting the control law performance.

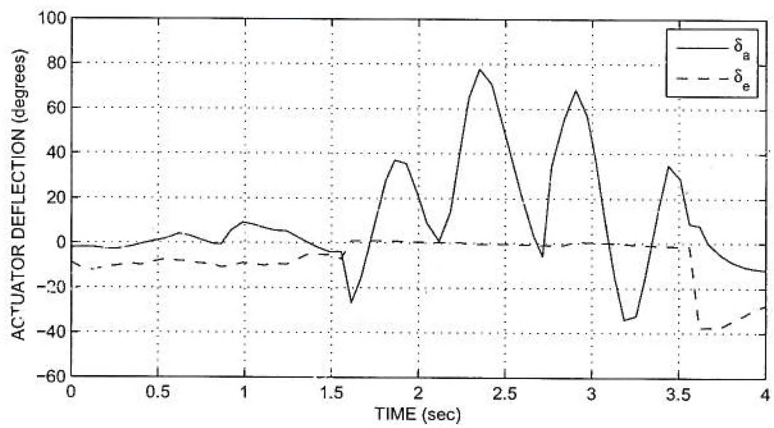


Figure 7: The actuator commands for the aileron and elevator show that the roll gain, k_ϕ, (aileron actuation) could be reduced and the pitch gain, k_θ, (elevator actuation) could be increased.

5 Conclusion

We developed and demonstrated a aileron roll control law that greatly improves the performance of the previous aileron roll controller in terms of tracking the original flight path. The key improvement was the implementation of an altitude hold functionality that tracked the desired pitch angle in addition to the desired roll angle. The proper understanding of the effects of inverted flight on pitch angle was key to successfully implementing the improved control law. This understanding of the effect of changing attitude on maneuver control will be vital for implementing aggressive aerobatic maneuvers for obstacle avoidance. Additionally, the degradation in performance from simulation to flight test will need to be addressed in future research.

One possible approach to solving the problem of altitude loss would be to develop a feed-forward algorithm for pitch angle that would anticipate the desired pitch angle, thereby reduce dependence on accelerometer uncertainties and the lag inherent in numerical integration. Further, the results from the flight tests might be used to refine the aircraft model used in the Matlab and Aviones flight simulation software.

References

[1] D. Shim, H. Chung, H. Kim, and S. Sastry, "Autonomous Exploration in Unknown Urban Environments for Unmanned Aerial Vehicles," *2005 AIAA Guidance, Navigation, and Control Conference and Exhibit*, pp. 1–8, 2005.

[2] L. Singh and J. Fuller, "Trajectory Generation for a UAV in Urban Terrain, using Nonlinear MPC," *Proceedings of the American Control Conference*, vol. 3, 2001.

[3] S. Griffiths, J. Saunders, A. Curtis, T. McLain, and R. Beard, "Obstacle and Terrain Avoidance for Miniature Aerial Vehicles."

[4] S. Park, J. Deyst, and J. How, "Performance and Lyapunov Stability of a Nonlinear Path-Following Guidance Method," *Journal of Guidance, Control, and Dynamics*, vol. 30, no. 6, pp. 1718–1728, 2007.

[5] S. Lindemann and S. LaValle, "Current Issues in Sampling-Based Motion Planning," *Proceedings of the International Symposium of Robotics Research*, 2003.

[6] E. Frazzoli, M. A. Dahleh, and E. Feron, "Real-Time Motion Planning for Agile Autonomous Vehicles," *AIAA Journal of Guidance, Control, and Dynamics*, vol. 25, no. 1, pp. 116–129, 2002.

[7] M. Mockli, "Guidance and Control for Aerobatic Maneuvers of an Unmanned Airplane," dissertation, Swiss Federal Institute of Technology, Zurich, ETH Zentrum, ML; CH-8092 Zurich; Switzerland, 2006.

[8] J. Hall and T. McLain, "Aerobatic Maneuvering of Miniature Air Vehicles Using Attitude Trajectories," *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, 2008.

[9] R. S. Christiansen, "Design of an Autopilot for Small Unmanned Aerial Vehicles," Master's thesis, Brigham Young University, 2004.

[10] D. Kingston, R. Beard, T. McLain, M. Larsen, and W. Ren, "Autonomous Vehicle Technologies for Small Fixed Wing UAVs," *AIAA 2nd Unmanned Unlimited Systems, Technologies, and Operations–Aerospace, Land, and Sea Conference and Workshop & Exhibit*, pp. 2003–6559, 2003.

[11] J. Craig, *Introduction to Robotics: Mechanics and Control.* Addison-Wesley Longman Publishing Co., Inc. Boston, MA, USA, 1989.

[12] B. L. Stevens and F. L. Lewis, *Aircraft Control and Simulation.* Hoboken, NJ: John Wiley & Sons, Inc, 2003.

[13] J. Hall, "Guidance and Control for Aerobatic Maneuvers of an Unmanned Airplane," dissertation, Brigham Young University, Provo, UT, BYU, Provo, UT 84602, 2009.

Presentation

ALTITUDE HOLD AILERON ROLL MANEUVER

1Lt Justin Mason
LtCol James Hall

Introduction

- Aerobatic maneuvers for miniature air vehicles (MAV)
- Altitude-hold aileron roll
- Flight simulations for concept validation
- Flight test demonstration

Trajectory Tracking

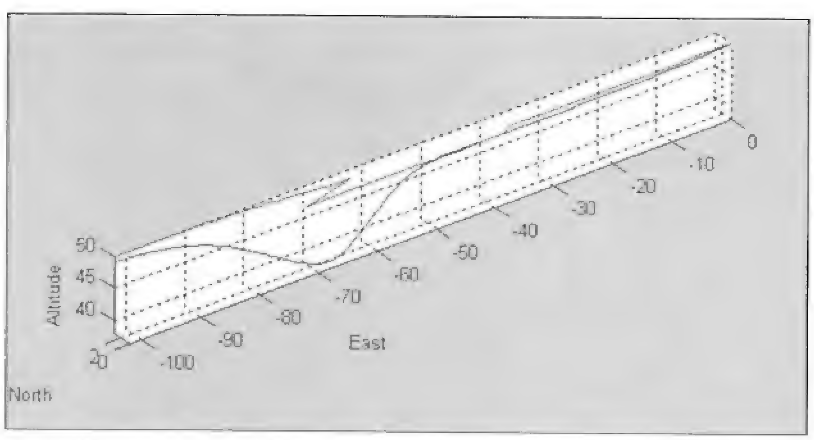
- Goal: maintain heading and altitude while completing a full rotation about the body reference frame X-axis
- Fifth order trajectory in bank angle

$$\phi_d(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5$$

- Only aileron commands

Trajectory Tracking

- Original method had significant altitude loss
- Need desired pitch angle for control law



Altitude Hold Aileron Roll

- Zero change in altitude (Navigation Eqn)

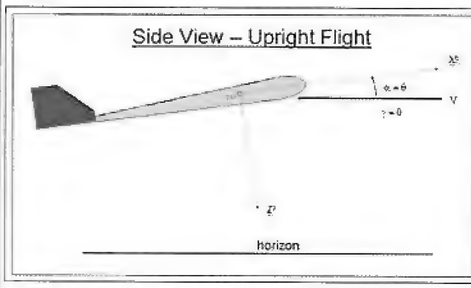
$$\dot{h} = U\sin(\theta) - V\sin(\phi)\cos(\theta) - W\cos(\phi)\cos(\theta) = 0$$

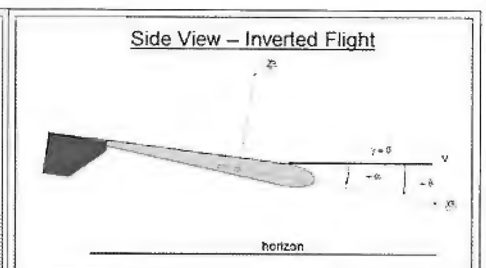
- Desired pitch angle from desired bank angle
- Includes elevator commands with existing aileron

$$\theta_d = \tan^{-1}\left(\frac{V\sin(\phi_d)}{U} + \frac{W\cos(\phi_d)}{U}\right)$$

Desired Pitch Angle

- When inverted
  - Angle of attack positive (wrt body frame)
  - Pitch angle negative (wrt inertial frame)
- Upright – θ_d positive
- Inverted – θ_d must still be positive





Control Law Changes

- Upright $-90^\circ < \phi < 90^\circ$
  - Elevator command negative

$$\delta_a = K_\phi(\phi_d - \phi)$$
$$\delta_e = K_\theta(\theta_d - \theta)$$

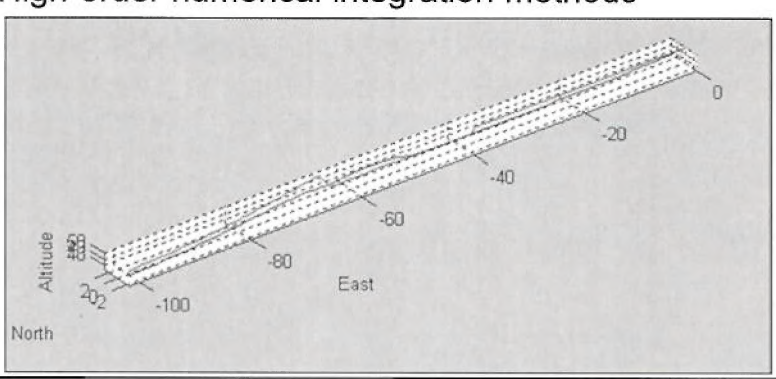
- Inverted $(90^\circ < \phi < -90)$
  - Elevator command positive

$$\delta_a = K_\phi(\phi_d - \phi)$$
$$\delta_e = -K_\theta(\theta_d - \theta)$$

- Logic switches modes when MAV is inverted

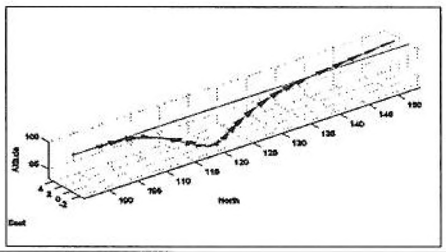
Matlab Simulations

- Matlab Simulink flight simulator
- Full, nonlinear equations of motion
- High-order numerical integration methods



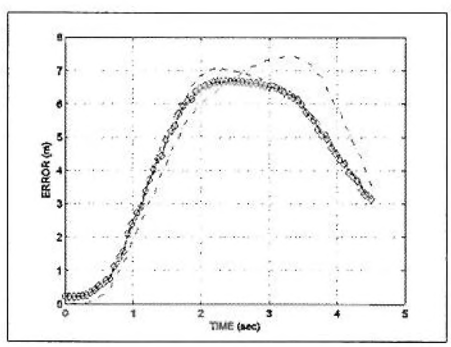
Aviones Simulations

- Aviones flight simulator results
  - Nonlinear equations of motion, RK4 integration
- Exact autopilot code in artificial environment
- Numerical integration of accelerometers
  - Introduced lag and sensor noise
- Less than 7 m altitude loss (50% improvement)



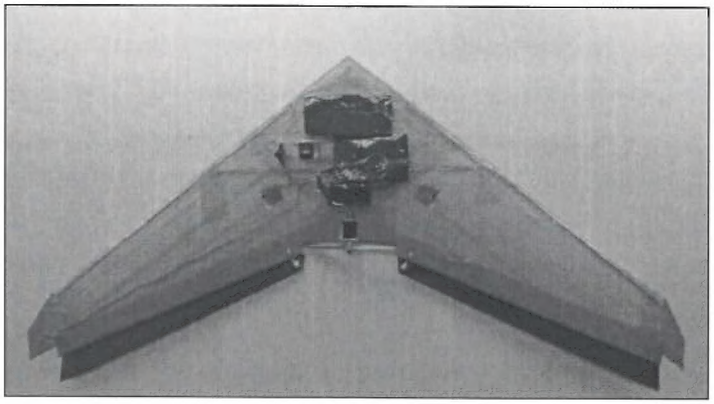
Gains

- Aviones flight simulator allows gain tuning
- K_θ = 0.7 provides best tracking
- More Gain
  - Less altitude lost
  - More variation from path
- Less Gain
  - More altitude lost
  - Less variation from path



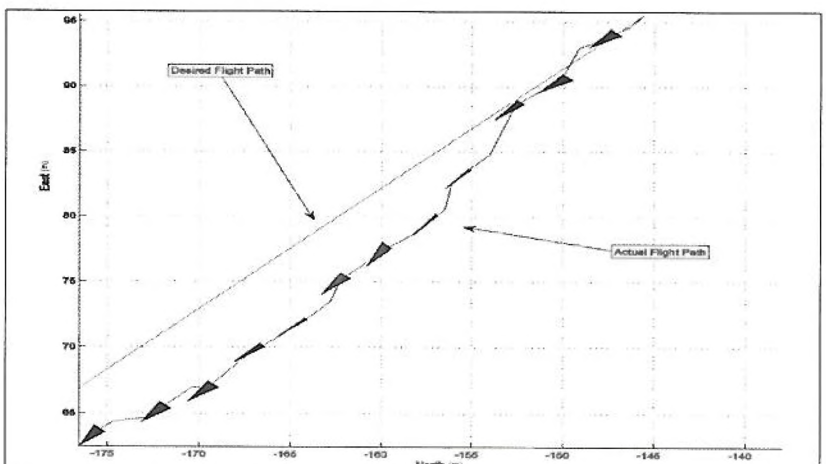
Flight Tests

- Zagi-style MAV with Kestral Autopilot
- Validated results from simulations



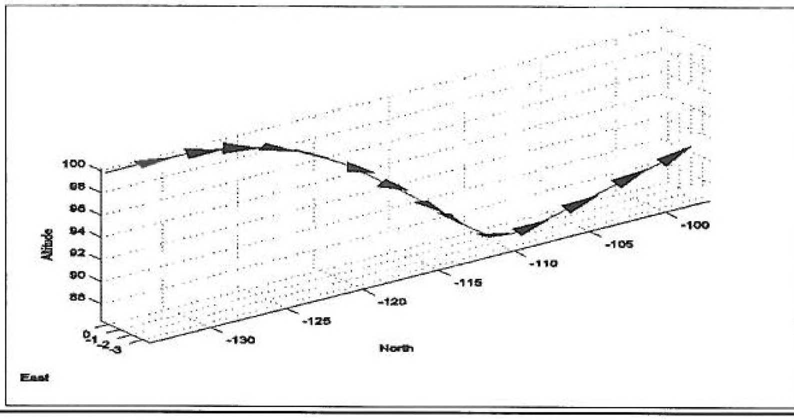
Flight Tests

- Validated results from simulations



Flight Tests

- Slower autopilot processor increased lag
  - Lost 12 m of altitude (25 m lost w/o altitude hold)
- Trouble when reacquiring next waypoint



Questions?